F15-Adaptive cornhole for persons with spinal cord injuries

Team: Make Cornhole Playable Again

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Executive Summary

The project's main purpose is to design and produce an assistive device that can enable spinal cord injury patients (Low cervical patients from C5~8 injuries) to participate in cornhole for recreational and rehabilitation purposes. To achieve the aim of the project, the device must successfully solve several design and technical constraints: adjustability to support a wide range of physical conditions across many patient groups, ensured safety for patient participation during product usage, and good power-to-weight ratio for the product that can provide sufficient assistance to allow users to throw cornhole bags.

To overcome several design and technical limitations posed for the following project, the function tree, morphological charts, house of the quality chart, stakeholder matrix, and criteria table are utilized to weigh and analyze potential solutions to inherent issues for the device. After active market research in commercially available products and communication with the clinician working at Shepard's rehabilitation center, two main designs are chosen to fulfill the project's goal. The first design uses a shovel attached to the user's forearm to help users with limited wrist and finger control easily pick up and throw the cornhole bag. The shovel is attached to a commercially available wrist brace that comfortably fits the user's wrist. The shovel design targets C6~8 patients who have some mobility in their arms and shoulder and has the ability to throw and drive an adapted vehicle. The second design uses an external assistance platform that users can use to gain assistance in throwing the cornhole bag. The platform uses a swing motion of the user's orthotic interface using the potential energy and gravitational pull to help users with limited strength to throw the cornhole bag. The second device targets patients with C5 injuries who lack mobility and strength in arms and shoulders and need assistance in throwing. They can only achieve independent movement through powered wheelchairs.

The main goal of the device is to enable the patients to participate in the recreational activity of cornhole. Therefore, the most crucial performance specification of the design is how much independence the product can give to the patients. The patient's independence will determine the success of the following design and make the product necessary in the market. The proof of concept for the following designs is achieved through a strict selection process among other designs and the measure of high functionality that can easily outweigh competition against other potential options on the market. Several pilot trials with the patient population with the prototype have been conducted to evaluate the success and failures of the following designs. The next step for the following devices is to make necessary adjustments for the final product to be used in rehabilitation.

Nomenclature

SCI/sci: Spinal Cord Injury

External Device: Subsystem of the cornhole adaptive system that gives the user the strength to throw the bean bag.

Shovel device: Subsystem of the cornhole adaptive system that allows imitates the hand in throwing and grabbing the bean bag.

Grip device: Subsystem of the cornhole adaptive system that allows the user to grab the shovel device.

NSCISC: National Spinal Cord Injury Statistical Center.

C5 – C8: Cervical Nerve

Main Body

1. Introduction and Background

The motive behind the project is the help those w spinal cord injuries to play the game of cornhole effectively. As is, many patients lack the ability to properly grip and control the bag, and some even lack control over most of their arm. While these levels of control vary widely, the majority lack fine motor functions in their hand to hold and throw the bag. This project will therefore aim to design and produce a fun assistive device to allow patients with spinal cord injuries to play cornhole as their physical therapy.

As previously stated, the main objective will be to aid patients in picking up and throwing the bag toward the target with relative accuracy. Specifically, the patient group will be those with lower-level spinal cord injuries, C5 to C8, currently residing at the Shepard Center. The product will be able to be used both indoors and outdoors.

Two main devices were developed, each with its use and purpose. The first device is the shovel device which allows the user to lift, hold, and release the bag while throwing. Since many patients lack control over their hands, the shovel will simplify the process by allowing them to scoop the bag and launch it. The second device is the external device and is intended to aid those who lack strength and control over their arms to throw the bag far enough. This device aids them by pushing the user's arm with enough strength to launch the bag toward the goal. Depending on the user's needs, these devices can be used independently or in conjunction.

This will benefit the patients as they will be the ones who directly benefit from the devices. It allows them to effectively complete a task or play a game that was initially much more difficult. This will also benefit the Shepard Center clinicians as the patients can play the game independently without their aid.

During the development of the device, many challenges were faced. During the prototyping of both devices, technical issues came to light and were difficult to solve. For example, the shovel underwent many modifications to improve its launch of the bag and its ability to scoop. Other challenges such as ensuring ease of use for the patients, as well as safety regarding the external device due to its method of function.

The next sections will discuss existing technologies and devices that function similarly and work to aid those with other tasks, as well as the requirements those have that ours will also need to have in terms of the customer and specifications. From there, the report moves into the market in terms of who this device is aimed towards as well as plans to look more closely at our target market. It then goes onto discuss the ideation process, and selection of our designs as well as the justifications behind them. Then it goes into the industrial design of the products as well as their feasibility testing, which leads to the final designs being used. The report then ends discussing the risk assessment, manufacturing, and the impacts of the device.

2. Existing Products, Prior Art, and Applicable Patents

The requirement for the following product is that it must assist the users to grab the cornhole bag and assist the user in throwing the bag. At Shepard's rehabilitation center, spinal cord injury patients use billiards cuffs and grasping cuffs to use gardening tools and participate in gardening activities presented in Figure 1. There are several commercially available cuff options for patients with spinal cord injuries. Sammon Preston Grasping Cuff is priced around $50~60 with and without wrist support. Figure 2 shows the US8966664B2 patent for a gripping aid designed to aid the elderly or patients with arthritis to grip items. Most cuff designs use Velcro and straps using a D-ring to allow users to adjust and wear the cuff with limited finger control. Also, the material used in the cuff is soft suede material that reduces the friction on the user's skin and irritations. The FEATOL wrist brace for carpal tunnel with adjustable wrist support brace with splints, shown in Figure 3, is the perfect example that can allow users with limited wrist strength to gain stability in the wrist and hands with the necessary safety requirements for patients. The brace is priced at around $18, which is highly economical and cheap. Therefore, the following product was chosen to be incorporated into the final design of the device.

Market research found that the most popular device used for assistance to throw for people are ball throwing scoops used for pet owners to throw balls necessary for pets. The related patents include EP3146838B1 Ball-throwing scoop for interaction with pets that uses a small shovel-like design to pick up and throw the ball to throw easily presented in Figure 4. The commercial standard for following interactive devices is priced around $15~45 depending on the quality and rigidity of the material used. The devices use lightweight high, density plastic for outdoor applications. Therefore, the prototype uses 3D printers to print a shovel design and different settings to find the necessary rigidity required for outdoor applications and using a 3D printer reduces manufacturing costs.

The combined price range for the two devices that allow users to grab and throw a cornhole bag is around $50~100. Therefore, the device must be priced in the lower range of $50~75 for marketability in commercial applications. Additionally, the following rehabilitation devices must be relatively cheap for patients' ease of access and usage. The existing products must be lightweight, highly durable, highly adjustable with limited finger control, and cheap to compete in the commercial market.

3. Codes and Standards

1. CFR Title 21 Part 890: This section of the CFR contains regulations for rehabilitation engineering and assistive technology devices, making it relevant to our project as it offers guidance on safety, performance, and regulatory compliance requirements for rehabilitation devices.

- Safety and performance requirements: To guarantee patient protection and proper functioning for therapeutic purposes, the cornhole rehabilitation device must adhere to the safety and performance requirements outlined in CFR Title 21 Part 890, minimizing the risk of injury or harm.
- Labeling and instructions for use: In compliance with CFR Title 21 Part 890, the cornhole rehabilitation device must be labeled and include clear instructions for use, ensuring that patients, caregivers, and healthcare providers understand proper setup, usage, and maintenance, thus reducing the risk of injury or misuse.

2. ISO 9999:2011: This international standard, titled "Assistive products for persons with disability – Classification and terminology," provides a comprehensive classification system for assistive products used by individuals with disabilities and establishes standardized terminology for clear communication among various stakeholders, such as manufacturers, healthcare professionals, and regulatory bodies.

- Terminology: This standard defines a common set of terms related to assistive products for persons with disabilities. By adhering to this standardized terminology, clear communication among stakeholders is facilitated, ensuring that documentation, labeling, and instructions for the non-electronic wearable device are consistent and easily understandable.

4. Customer Requirements and Engineering Design Specifications

The cornhole aid tool must be effective at allowing the user to be able to pick up the cornhole bag and toss it at a minimal distance of 2-3ft. It is necessary that the tool be safe and comfortable for the intended use and when used incorrectly. Many patients with spinal cord injuries don't have the ability to feel pain on their bodies therefore, the tool should not pinch, bruise or cause bodily harm in any way when used for any amount of time. The task revolves around enabling the user to become as independent as possible while playing cornhole, and so the tool must be intuitive to use for patients that suffer from C5-C8 SPI to the point that they won't need assistance or very minimal if any. Similarly, the tool must be able to be used passively and be simply designed to not discourage the user. Most therapeutic and orthopedic devices are found to be too expensive for the average consumer. The design of the cornhole aid tool must focus on reducing cost associated with the access to the tool such as it must be easily accessible to buy for clinics and in common retail stores, purchase price must be less than $100 dollars, made of durable and inexpensive materials, easily reparable with easily replaceable parts. To accommodate most users, it must be easily adjustable to the individual's height and size while also easy to transport and store.

Such customer requirements were selected with the use of House of Quality and the Customer Requirements tables provided in the appendix. There were many considerations for selecting the customer requirements as they needed to reflect the interests of the patients, the staff working with the patients, and the interests of the Craig-Nielson Foundation. To begin with, there needed to be a focus on making sure that the patient was able to access the beanbag in a safe manner in order to throw it an arbitrary distance. This consideration outlines customer requirements 1 to 3 in Table B-1. It was important for the patient to be able to use the device in a safe manner during playtime as it enables for exploration of different throwing techniques when playing cornhole. Another consideration was for SCI patients with C5-C8 injuries were able to use a simple passive device that enabled a path towards maximum independence. This consideration outlines customer requirements 4 to 7 in Table B-1. The clinicians expressed their enthusiasm for a device that enabled maximum independence for the user whether they were using both devices during recreational time or just one of the two devices. Furthermore, the devices must be accessible to both the public and the clinics at a price below current devices on the market. This consideration outlines customer requirements 8 to 11 in Table B-1. There was great emphasis by the Shepherd Center to be able to create a device that was inexpensive and available for purchase by the public. This also aims to aid those who cannot afford expensive devices that are usually in the four-figure price range. Another consideration for the customer requirements was to make both devices from durable but inexpensive materials. This consideration outlines customer requirements 12 to 13 in Table B-1. Finally, a consideration that needed to be addressed was for both devices to be easily repairable with easily accessible parts for repair and for easy storage of these devices. This consideration outlines customer requirements 14 to 16 in Table B-1. This requirement was created to ensure that the device maintained a certain level of complexity in storage and reparation. This also enables the user to store the devices in storage facilities already designated for patient equipment and eliminate the need to allocate unessential space for a custom device.

Stakeholders with the most notable influence are listed bellow in Figure B-1. Stakeholder Matric data. They are more notably the ones who dictate to what the team will give most focus and the ones who provide the funding. Recreational therapist and Project sponsor are seen to have the most influence and importance when it comes to decisions made by the team, as seen below on the Stakeholder 2X2 chart on Figure B-1. They both provide the most advice and best insight into the team's deliverable and expectations. The project sponsor provides the funding while the recreational therapist provides the best insight into what the users want and need. The least influential stakeholders are considered to be the government and insurance companies due to the simplicity of the device and the low cost, there aren't many factors involving the assistive device that involve these two entities. Patients range in the middle as they are important to the project but don't have much influence compared to the physical therapist who speaks on their behave.

To not discourage the user from attempting the activity of playing cornhole, it is important for the assistive device to be simple while also promoting as much independence as possible. For example, a device used to hold or grasp the cornhole beanbag must be able to successfully assist in holding the bag for the duration of the game of cornhole without difficulty. This metric can be measured by determining how much surface area is overflowing from the developed holding device. This assistive device will be specifically developed for cornhole, so it will need to have some sort of measurement for how effective it is at picking up the beanbag. This metric can be measured through trial and error on how effectively a patient or individual fully picks up a beanbag off the floor an arbitrary number of times. This will allow to perform a statistical analysis on the probability of how effective the device is at picking up the beanbag. Another function that the holding device must perform is assisting in tossing the beanbag. This metric can be measured by calculating the projectile angle at which the beanbag leaves the shovel and the total distance travelled. Depending on how steep this angle is, it will determine how effective it will reach the cornhole board.

While on the topic of displacement, the external assistive device arm must perform the same function of helping users toss the ball at a desired distance. This metric will be measured by how far the external arm stabilizer can help propel a patient's arm when they go to throw the beanbag. To acquire these measurements, multiple test trials will be needed. Another function that will need to be measured is the number of degrees of freedom the weighed arm stabilizer allows itself to go before stopping. A way of measuring this function is to perform impact tests and analyze the force generated upon a damper that will be installed on the device. The variation in force will determine the bounce back of the arm, and how effective it is at stabilizing and dampening the impact.

Both the external arm stabilizer and the shovel must be able to be adjusted for the user size as not everyone can fit in a one size fit all. This function can be measured by obtaining a reasonable average height and weight of different populations and designing the optimal metrics for these assistive devices. This device must also be comfortable for the user. A way to measure this metric is to monitor the body, temperature and perspiration that comes from the individual by testing different materials. Comfort is especially important due to the fact that target users with spinal cord injury are not able to regulate their body temperature as effectively. Finally, the device must be easily and intuitive to put on as well as lightweight for cornhole use. A way of measuring these metrics is to perform tests on how easily a SPI patient can put on the device by timing how long it takes them to do so. A method to measure how effectively a lightweight device interacts with a user is to vary the material used to produce prototypes. This will enable the collection of data based on how the user response to the weight of the device. These are the functions that the entire assembly will have to perform for the user.

Constraints need to be considered for the entire assembly of the device. This is because this device must accommodate not only the user, but also the stakeholders that are interested in the development of this device. A constraint related to the production of the device is making the device with breathable materials. Materials such as nylon polyester cotton and felt allow for the skin to easily breathe and maintain a regular temperature. This will enable longer play times than with non-breathable materials. Another constraint posed for the device is to make a system that is easy for the user to put on by themselves. The mayor goal of this assistive device is to allow users to achieve as much independence as possible. For this reason, a Velcro strap design will enable users to use their other extremity to easily and securely engage with the device. Furthermore, the device must also be made of lightweight material, which is another constraint posed by the development of the device. The device could be made from ABS plastic, as well as a mixture of light fabrics mentioned previously.

Other constraints that need to be addressed are the cost of the device, the rotational motion of the external device, the transportation and storage of the device, and the safety factor of the device. The cost constraint of developing a mobility assistance device is addressing the types of material used as well as the amount of parts being used for development. A solution to this constraint is to manufacture less parts, as well as utilizing some form of injection molding to use plastic parts for the entire assembly. There would need to be parts that are not made from plastic, but for the most part, the device could be manufactured with inexpensive materials. The constraint of rotational motion is that the device needs to accommodate different directions of motion. A potential solution to this constraint is to develop ball joints that will enable potentially unlimited forms of directional rotation. The constraint concerning transportation and storage is that it must be convenient for the user if they plan to store and play corn hole for therapeutic reasons. Usually, the storage unit in a clinical facility is already composed of many therapeutic devices that will clutter the space. It is the duty of the developer to try and accommodate for easier storage and transportation. A potential solution would be to either minimize the amount of material used for the device production or to create a device that can be taken apart into several pieces. Finally, another constraint is making sure the rotational portion of the device is controlled safely. It is important to keep the users safe as well as keep the stakeholders free of liability issues from the questionable safety of the device. A solution to controlling the safety of the advice would be to insert cushioning material in needed areas as well as bumpers to limit the movement of the rotational portion of the device. All these constraints have been taken into consideration when developing designs catered towards mobility assistance during the game of cornhole.

5. Market Research

Market research is an important step in determining demographics, pricing, market sizes, competing products, and design changes. Initial research was done through interviews with therapists in order to acquire information regarding the patients who would use the product. Additional research was done via the internet to determine the market size based on the information from the therapist, focusing mainly on rehabilitation centers in the country who focus on SCI patients. The internet was also used to determine a fair price range based off competing products, as well as discussion with therapists at the Shepard center. Research via feedback based off prototype designs and use from patients was also done during the prototyping stage.

The target demographic for the adaptive cornhole device is patients suffering from incomplete tetraplegia or C5 to C8 spinal cord injuries. According to NSCISC, approximately 46.8% of sci patients have incomplete tetraplegia. The market size would include all individuals within this demographic and subsequent SCI rehabilitation center. According to NSCISC, approximately 243,000 to 347,000 individuals suffer from SCI in the United States. Considering an approximation of 295,000 individuals having sci and a 46.8% percent of incomplete tetraplegia, approximately 138,060 individuals in the United States would be in the target market of the products. However, the actual number of individuals who visited a SCI rehabilitation center this year is much lower. According to the Shepherd Center website, there are 876 inpatients every year. There are also 69 current sci rehabilitation centers within the United States. Therefore, one can make an estimation based on the number of inpatients within all SCI centers to find a reasonable market size.

The targeted price for the entire cornhole system is $180. The system will be made up of 2 devices with their own pricing goals. The shovel device was aimed to be around $25, and the external device to be around $155. Compared to current solutions, these prices still manage to be reasonably lower than competitors. An exoskeleton arm which would replace the external device would range from $300 to $5000. The standard wrist orthosis device, which would replace the shovel device, ranges around the same price. Moving forward, the go-to-market strategies for the adaptive cornhole device will include email and online marketing strategies and poster advertisements within centers.

The market research has allowed changes to the initial ideation and the prototype currently in development. The braces function on the shovel device, and the entire external device has been added to accommodate a larger demographic. A cheaper design has also been chosen to compete with the current market and for larger demographic concerns.

6. Concept Generation, Selection, and Iteration

In order for the proposed device design to be effective at assisting users in playing cornhole, it must fulfill several functions. The device needs to assist users in picking up and lifting the cornhole beanbags off the ground or wherever the cornhole bags are placed. It needs to aid the user in tossing the bags far enough to reach its target while doing so accurately. While using the device, it must be stable, intuitive and easy to use independently. Additionally, it needs to be comfortable and adjustable so that it may accommodate a wide variety of users while being used for prolonged periods of time. Using these functions as a basis for designs, many different concepts were made to fulfill the required functions.

Providing support:

- A device with adjustable armrests and a support bar to assist in throwing the beanbags.
- A device with comfortable and safe user face
- A device with a motorized mechanism to assist in throwing the beanbags.

Allowing the player to throw the beanbags:

- A device with a lever-operated mechanism to throw the bags.

Ensuring stability:

- A device with a wide base for stability.
- A device rigid enough to support needed weight

Providing adjustability:

- A device with adjustable height, length, width and tilt to accommodate different users and playing positions.
- A device with a tilt mechanism to adjust the angle of the playing surface.

The morphological chart as seen in Appendix B: Table 1 is used to create more specialized design concepts to fulfill the various designs functions. Such concepts went under a feasibility study and from this study, a multitude of different integrated concepts from the morphological chart were created and can be seen below:

Wrist, hand assistant:

- Mechanical Clamp Design: This is designed for patients that have limited to no hand/fingers control (Figure C-1).
- Shovel Design: A shovel attached via a wrist strap used to pick up and throw the cornhole beanbags (Figure C-2).
- Modified Shovel Design: Simple short shovel design to allow user to easily toss the bag off scoop with minimal force. The safety straps are designed with comfort in mind made from breathable fabric (Figure C-3).
- Shovel with Wrist Brace: A scoop with an attached pre-existing wrist brace for maximum comfort (Figure C-4).
- Bendable Shovel Design: Users can bend open/close the shovel by pulling a string attached to the shovel (Figure C-5).
- Underactuated Gripper Design: Users can close/open the gripper's finger by pulling a string attached to the gripper (Figure C-6).
- Hydraulic Actuating Glove: It comprises of 5 actuators, one for each finger. Constraints which allow for full finger-knuckler knuckle motion. Can be used to open and close all finger joints (Figure C-7).

Elbow assistant

- Elbow Actuator: Hydraulic actuator that is strapped to the forearm and bicep. Allows user's elbow to extend and bend (Figure C-8).
- Motor roller: A motor attached to the arm pulls the hand or wrist (Figure C- 9).
- Fixed belt length design: Due to the fixed length of a belt, rotating the shoulder forward will cause the entire arm to bend (Figure C-10).
- External Device: Swing like system that allows the user to be assisted in the tossing motion of the bag. (Figure C-11).
- Pressurized Mobility System: An inflatable hand device that when inflated allows the user to straighten arm. The airbag allows for pressurization. (Figure C-12).

All figures and tables can be found in Appendix B: Concept Generation, Selection, and Iteration.

7. Industrial Design

Both devices were designed with the intention of being as simple as possible while still being able to accomplish what they were designed to. The benefits of keeping the designs simple is it improves the ease of manufacturing. Additionally, both devices were designed with comfort and ergonomics in mind. The shovel device uses an off the market arm brace that has been tested for comfort. The external device underwent many different updates and changes in order to improve its ease of use and comfort. It has a single interface with the user and is shaped and padded for comfort. Aesthetics also played a role in design as these are meant to be recreational aid devices, so keeping a playful look in mind was necessary.

Visual hierarchy was also used in the design of both of these devices. For the shovel device, as implied by the name, it is shaped like a shovel, making it obvious how it's meant to be used. This will allow for the user to quickly understand that the intent is to scoop the bag and launch it out of the shovel. Additionally, the attachment system of the device is a simple arm brace which the users will be familiar with, making it clear how it's meant to be attached as well. The external device is broken into two parts, the base and the interface. The interface is the piece that pushes the arm and is located at around shoulder to elbow height of a sitting patient and protrudes out to the side of the device. It can be switched to the other side depending on the user's dominant hand. It is shaped in a curve and is padded, making it clear that the arm is meant to go here. The rest of the external device is a base focused on ensuring the device is stable and safe to use.

Branding and logos were easily done using the sponsors logo, the Craig Neilson foundation. Their logo, along with the Georgia Tech logo, were used on both devices. Additionally, the colors of the devices were chosen so that they would complement the logos, as well as promote the perception that these are recreational devices.

8. Feasibility Assessment

To validate the feasibility of the shovel design, empirical tests were conducted with ten able-bodied subjects (5M/5F), who were all novel users. The protocol involved three practice trials and three attempted throws for each participant. The vertical distances from the cornhole target were measured in feet, and the subjects provided feedback on a 0-10 scale, comparing the device-assisted throw to a hand throw. The results can be found in Table D-1. Overall, the results demonstrated that the assistive device effectively helped participants play cornhole, with minimal performance difference compared to a hand throw. Most ratings indicated a positive user experience, suggesting the device as a feasible solution for patients with low-cervical nerve injuries (C6-C8) to play cornhole.

Additionally, a numerical evaluation of the device's feasibility was performed using MATLAB in Code D-1, focusing on the holding, and tossing mechanisms. For the holding mechanism, the ability to hold the cornhole bag was analyzed by adjusting various parameters, such as the friction coefficient and the shovel's bend angle. The results showed that the friction force was sufficient for securing the cornhole bag when the shovel angle is 60 degrees, and the friction coefficient is 0.6. For the tossing mechanism, a kinematic analysis was conducted to ensure controlled and smooth motion during the toss. The evaluation involved changing the shovel's angle, radius, and target distance to simulate different tossing scenarios. The friction force was compared with the escape force required to toss the bean bag, and it was found that when the target distance is 3 m, the escape force at the required rate of fire is greater than the friction force.

To validate the feasibility of the external design, numerical values were first calculated to evaluate the performance of the external device. Using the launch angle values and the distance calculated in the shovel design process, the team calculated the torque required to achieve the terminal velocity necessary for the cornhole bag to travel the necessary distances using Equation D-1. The torque needed to achieve the exit velocity was 54.7Nm. To evaluate the feasibility of the device, pre-existing research documents were carefully analyzed. According to the study conducted at the Rochester Institute of Technology, the average men’s and women’s push strength at 1.3m was around 300N and 200N [4]. Therefore, half of the average push strength is needed for users to help patients push their arms to throw cornhole bags to the desired distance.

Then, an experiment was conducted for empirical evaluation of the external device. Ten Able-bodied Subjects (5M/5F) participated in the prototype experiments and were all novel users. They assisted the same person in evaluating the feasibility of a clinician helping patients to throw desired distances. Three practice trials were conducted before testing; each person had three attempted throws. The distance between the cornhole target (placed 10 ft) and the cornhole bag was measured, and the participants gave feedback on a 0 ~ 10 scale to compare to a hand throw. The results are presented in Table D-2. As the results show, the external device showed great numerically and empirically feasibility, making the concept design for the external device successful.

9. Final Design Solution

The two final design solutions for the External device and the shovel device have been iteratively processed through three prototype phases. The External device is used for those patients with a complete inability to power their tossing arm using their own muscular strength, specifically those suffering from C5 spinal cord injuries, or those who have difficulty applying enough power to throw the bean bag at their desired distance. The patient first aligns their wheelchair and body to the side of the External device and then places their arm into the arm rest plate. The user then grips the bean bag with the help of the shovel device or with their own hand. A therapist stands directly behind the patient and the external device and places their left hand on the handle and their right hand on the top of the frame. The therapist then thrusts forward their hand allowing the patients arm to also move forward and mimic the tossing motion of a common cornhole toss. The final design for the External Device is shown in Figure E-1. The Shovel device can be used in this process and is simply a device that allows for gripping for those patients with the inability to hold the bean bag on their own. The final design for the shovel device can be seen in Figure E-2

The external device is made up of two subsystems, the frame, and the launching arm. The frame allows for vertical adjustment of the throwing arm so that users can adjust the height for their needs, and it also provides stability to the entire system. The launching arm is used for transferring mechanical energy from the therapist's body to the users tossing arm. Furthermore, both systems can be broken down even further into their individual components. These components can be seen in Figure E-3 and are composed mainly of adaptors, bushings, and clamps to allow for a smooth rotary turn for the device.

The three prototype phases for the external device had substantial changes for each progression. The first prototype was powered through potential energy with the use of weights and a potential motor for pulling the throwing arm back into its initial position. The frame was composed of PVC tubing and the tossing arm was made of MDF and had 20lb weight attached to the top. The second prototype discarded the use of weights and a motor to power the device and was instead powered by having the therapist push the device. The PVC frame was replaced by metal to be able to withstand the high forces involved. The third prototype made use of slotted holes in the metal framing to allow vertical adjustment of the tossing arm and changed the tossing arms design to allow for a more efficient transfer of power from the therapist to the user. The final design solution used all the elements from the third prototype. However, the final design was painted black for aesthetic purposes and had a slightly extended tossing arm.

The Shovel design involved 3 major design iterations with significant changes in between each iteration that helped improve the device. The first prototype involved a 70-degree angle curvature on the scoop component which was calculated to allow the beanbag to be tossed at the most optimal distance. A brace support component was attached to the scoop to allow the brace to be mounted to the scoop. A brace support adaptor was made to easily attach the brace to the brace support. An image of the first prototype and brace support adaptor can be seen in Figure E-4. Through testing, it was discovered that the launch angle was too large and so it was reduced to 45-degrees for the second iteration while also adding a curvature to the brace support component for ergonomic comfort. The overall length of the scoop and the brace support had an increase of length to improve on comfort and ease of use. The scoop shape was also modified to be more cylindrical to better hold the beanbag in place. The second prototype iteration can be seen in Figure E-5 For the final iteration, the angle curvature was changed once again to 65-degrees and the edge of the scoop was modified to a pointed edge to improve the shovel's ability to scoop the beanbags off the ground. The final prototype can be seen in Figure E-3 and the adaptor shown in Figure E-6

The Final design for the external device underperformed in its final state. The reason for this underperformance was its inability to allow for the arm rest plate and the users arm to remain in perfect contact throughout the entirety of the tossing motion of the arm. The cause of this is due to the shoulder joint and the pivoting rod of the tossing arm not aligning on the same axis. This causes slippage on the arm rest plate and the patient's arm which causes discomfort and poor contact. The external device is also unable to be used solely by the patient. This is a deviation from the original requirements, as the patient was originally supposed to use the external device solely by themselves with no help from a therapist. The External Device also still requires the patient to slightly lean into the device to some extent to allow for proper contact between the arm rest plate and the patient's arm. This is also a deviation from the original requirements and a failure of proper design. Despite its downfalls the External Device was still able to allow for a decent level of power transfer and ease of use for patients that have the ability to slightly move their upper body extremities. Again, however, patients with absolutely zero strength are unable to use this device in its final state efficiently.

The Shovel device performed on par with its original requirements. The device can be used by those with the inability to grip the bag properly and allows the patient to throw the bag at respectable distances. The shovel device slightly deviated from the original requirements due to its inability to pick up the bags from the ground at a highly successful rate. Although it is possible, there was a slight level of underperformance on that front. Overall, the Shovel device performed in a desirable scope with respect to the original requirements.

10. Risk Assessment, Safety, and Liability

The safety and liability concerns for the shovel device and external device were crucial during the design process. Potential risks were assessed using Failure Mode and Effects Analysis (FMEA) tables, which can be found in Table F-1 and Table F-2.

For the shovel device, risks include detachment of the scoop, cracking of the adaptor material, loosening of fastening bolts and nuts, and tearing of the brace material. Mitigation measures include using stronger materials, implementing a 10% infill with a gyroid pattern, using PETG material, employing locking nuts and adhesive, and reinforcing the brace. These actions aim to minimize bodily harm while ensuring a positive user experience.

The external device's FMEA table highlights risks such as the swing structure's fracture and ground platform's instability. Recommended actions include accurately calculating the user's arm and force load, using iron cast with a high elastic modulus for beams, and employing lighter materials for the swing. For the ground platform, extending the base parallel to the swing and changing the swing's power source are suggested for improved stability.

Risk, safety, and liability concerns significantly impacted the development of both devices. Design controls, such as stress testing, proper material selection, and secure connections, were implemented to address these concerns and ensure reliability and safety. Stress tests were conducted using SolidWorks simulation software, with a pressing force of 300 N and an arm weight of 5.5 kg. The simulation results indicated a factor of safety (FOS) greater than 100 at the connection between the swing part and the platform, demonstrating the device's reliability and safety. The simulation result is in Figure F-1.

11. Manufacturing

The final design solution can be easily manufactured for the eternal device. Most of the components for the external device are all available on McMaster and Home Depot's website. The only components not available are the adaptor, the shovel device, and the arm rest plate. These components can be found in Figure G-1 and are all 3-D printed components. The components are assembled solely through the use of bolts and nuts and require the proper fabrication tools such as a torque wrench and an Allen wrench. The shovel device can be made in high volumes for extremely cheap prices through the use of a 3-D printer. The brace portion of the shovel device is bought from an external source for relatively cheap prices in bulk. Once the shovel device is 3-D printed, fabrication is extremely rapid and takes only four bolts to fasten the entirety of the system together.

The use of PLA for the shovel device allows for rapid building and also allows the manufacturing costs to be relatively low. The use of PLA in a direct injection extruder is also an option for mass volume manufacturing, however this requires the use of extremely expensive machinery and metal molds. The external device is built from materials that are extremely easy to use and fabricate. The use of T-slotted framing rails in the tossing arm has ensured the manufacturing process is straightforward and reliable. The quality requirements for the shovel device are vital to the proper functioning of the product. The infill of the 3-D print must remain higher than 20% to allow for the device to withstand the high forces of throwing a bean bag up to 20 feet plus. Tolerances for the adaptor can be found in Figure G-2. Tolerances for the shovel device can be found in Figure G-3. Tolerances for the arm rest plate can be found in Figure G-4. The external device and the shovel device currently must be stored indoors as they are not rated for long-term outdoor storage. The materials selected can erode and degrade due to weather impact. The Production cost analysis is shown below for both the external device and the shovel device.

12. Environmental, Societal, and Sustainability Considerations

As analyzed in Table 8, several positive social impacts can result from the following product. The assistive device enables the patients to participate in recreational activities that were limited in participation due to their physical condition. The constant movement and improved throwing motion can significantly affect the user's arm and shoulder movement mechanics. Continuously using unused muscles can lead to rehabilitation effects for the patients. The rise in recreational physical activities keeps the patient active and enhances the experience at the rehabilitation center. Several studies show that functional physical movement is highly beneficial for mental health, so this product can also improve mental health for patient groups in the centers. The upgraded patient experience can lead to good feedback and recognition for Shepherd Center, which aims to provide a positive experience for patients during their treatment. Also, the increase in patient independence can reduce the workload for clinicians working in the centers, which leads to a good work environment for workers at the Shepherd Center. The general enhancement in work and patient experience at the center can create more funding opportunities for the rehabilitation center and increase awareness of the necessary treatments needed for spinal cord patients.

Some negative social impacts can result from the following products. Automating recreational activities can lead to reduced clinician labor, reducing job opportunities for the workers at the centers. To prevent the following impact, there is heavy involvement from the clinicians during the production stage of the product, and the clinician's required presence in piloting experiments increases the involvement of staff members at the center. The external device requires the clinician's involvement in the throw of the devices, so the following design alleviates the risk of drop in employment. Also, the device's failure during product use can lead to injuries for the patients and reduced interest and passion for patients in rehabilitation activities. Therefore, the following device will be heavily and thoroughly tested and piloted before patient participation at the centers.

13. Conclusions, Future Work

As this semester comes to an end, there are several conclusions that can be drawn from the adaptive cornhole project. There were two prototypes produced for the patients at the Shepherd Center. The devices were the adaptive shovel and the external device where each had its purpose for the specific spinal cord injury. It can be concluded that the adaptive shovel was much more effective in assisting patients with spinal cord injuries than the external device since the shovel did not require any moving parts. What made the external device difficult to function at its optional state was finding a single option that worked for everyone, which was a near impossible feat to accomplish. Future work includes sending these files to the Craig Nielson Foundation for further testing and evaluation. Improving the external device is also something important that needs to be done so that it can help patients with minimal strength in their shoulder region.

14. Team Member Contributions

Sufiyan Ahmed: Wrote the introduction, the market research section, and the industrial design section. Additionally aided in prototyping/testing, as well as presentation design. Was also responsible for updating BOM and maintaining documentation.

Min-Geun Park: Wrote the Feasibility Assessment and Risk Assessment section. I was responsible for creating the majority of prototypes, designing the poster, and crafting the presentation. Additionally, I conducted all the SolidWorks simulations to ensure the design's reliability and safety.

Diego Munoz-Reina: Finance Manager for project. Worked on customer needs, design concept ideation, final design solution, general revision and editing of report, design sketches, SolidWorks files for shovel device, Defined Stakeholder's interests and importance along with the corresponding charts/tables. Worked on criteria table and Morphological Chart. Created all fabrication package drawings and assemblies for shovel device, fabrication package document work, aided in prototyping/testing for all prototypes and presented for all presentations.

Jesus Lara: Co-Project Manager for the project. Worked on some design sketches and ideas for the adaptive shovel. Worked on the engineering specifications and house of quality for the device. Worked on the Bill of Materials, updated the engineering requirement section to reflect the newly updated progress of both devices.

Sanghyub Lee: Worked as a Sponsor Liaison, Scheduled and organized meeting with the clinician and visit to Shepard's rehabilitation center; wrote executive summary, existing product and patent research, societal consideration, and conclusion sections. Edited and organized the overall report. Participated in prototype manufacturing

James Boatwright: Wrote market research, created solidworks files for external device, created pressurized system ideation, Co-Project manager for the team, proposed shovel device idea to team. Created solid works files for all external device iterations. Created fabrication package drawings and assemblies for External Device, Fabrication Package document work, presented for all presentations to date, Expo Liaison work, was present for majority of prototyping work and help contribute to prototyping

15. References / Citations

[1] M. Fehlings, B. Kwon, A. R. Vaccaro, and F. C. Oner, *Neural Repair and regeneration after spinal cord injury and spine trauma*. Amsterdam: Academic Press, 2022.

[2] N. Uab, *NSCISC*. [Online]. Available: https://www.nscisc.uab.edu/. [Accessed: 08-Feb-2023].

[3] "Shepherd center," *Atlanta Brain and Spinal Cord Injury Rehabilitation Facilities | Shepherd Center*. [Online]. Available: https://www.shepherd.org/. [Accessed: 08-Feb-2023].

[4] "Human Strength Data Table." *Edge RIT*, http://edge.rit.edu/edge/P17708/public/.

Appendix A: Existing Products, Prior Art, and Applicable Patents

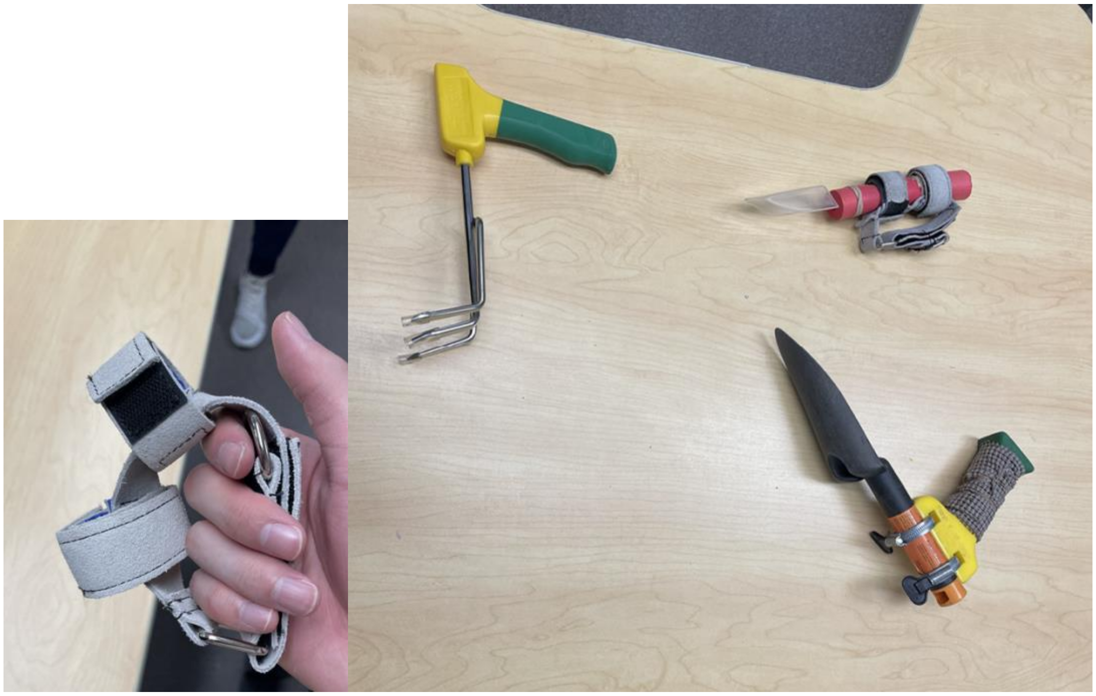


Figure A-1. Gripping cuff and Gardening tool used in Shepard's Rehabilitation Center

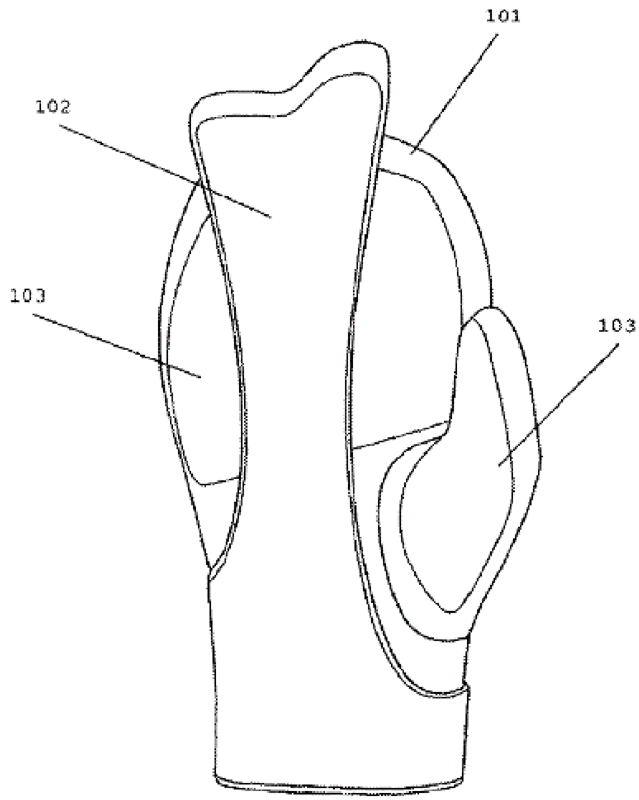


Figure A-2. US8966664B2 patent for a gripping aid

Figure A-3. FEATOL wrist brace for the carpal tunnel

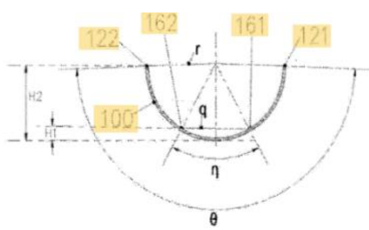


Fig. 3

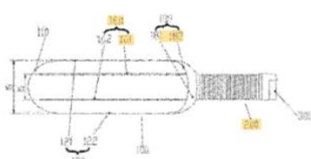


Fig. 4

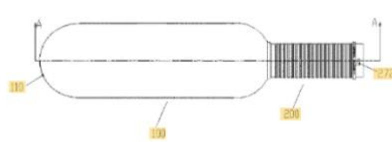


Fig. 5

Figure A-4: EP3146838B1 patent for Ball-throwing scoop

Appendix B: Customer Requirements and Engineering Design Specifications

Table B-1: Stake Holder Matrix data

Stakeholder	Interests	Impact/Effect	Importance	Influence
			Most Important 1	Least Important 5
Project Sponsor (Neilsen Foundation)	Provides team with guidance	High	1	1
	Adresses the needs of user	Medium	1	3
	Provides the projects budget	HIgh	1	1
	Cares for wellbeing of patients	High	2	2
	Devotes time into project	High	2	2
	Provides resources	High	1	1
Recreation Therapist (Hallie Wright)	Provides team with guidance	High	1	1
	Cares for wellbeing of patients	High	1	1
	Devotes out of work time to help team	High	2	2
	Provides resources	High	1	1
Georgia Institute of Technology	Wants students to succefully finish cource	Medium	3	4
	Provides resources to help students	High	1	3
Team Members	Succesfully pass course	High	1	1
	Succesfully help SCI patients	High	1	1
	Devotes large amount of time	High	1	1
Government regulations	Regulates and controls safety of products	High	1	1
SCI patients/users	Use the developed cornhole device	High	1	1
	Cornhole device favorability	High	1	1

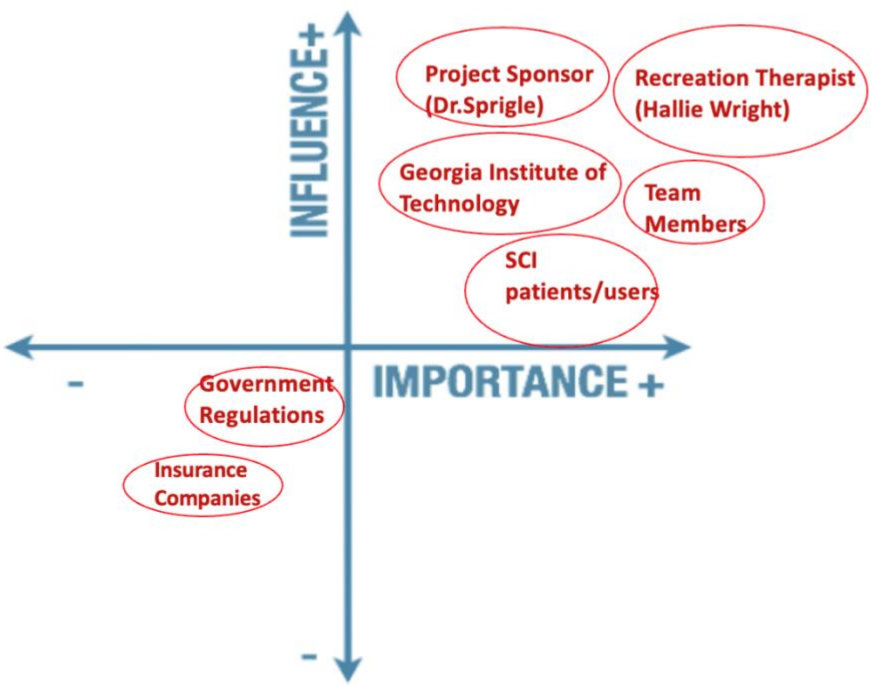


Figure B-1. Stakeholder 2X2 chart

Appendix C: Concept Generation, Selection, and Iteration

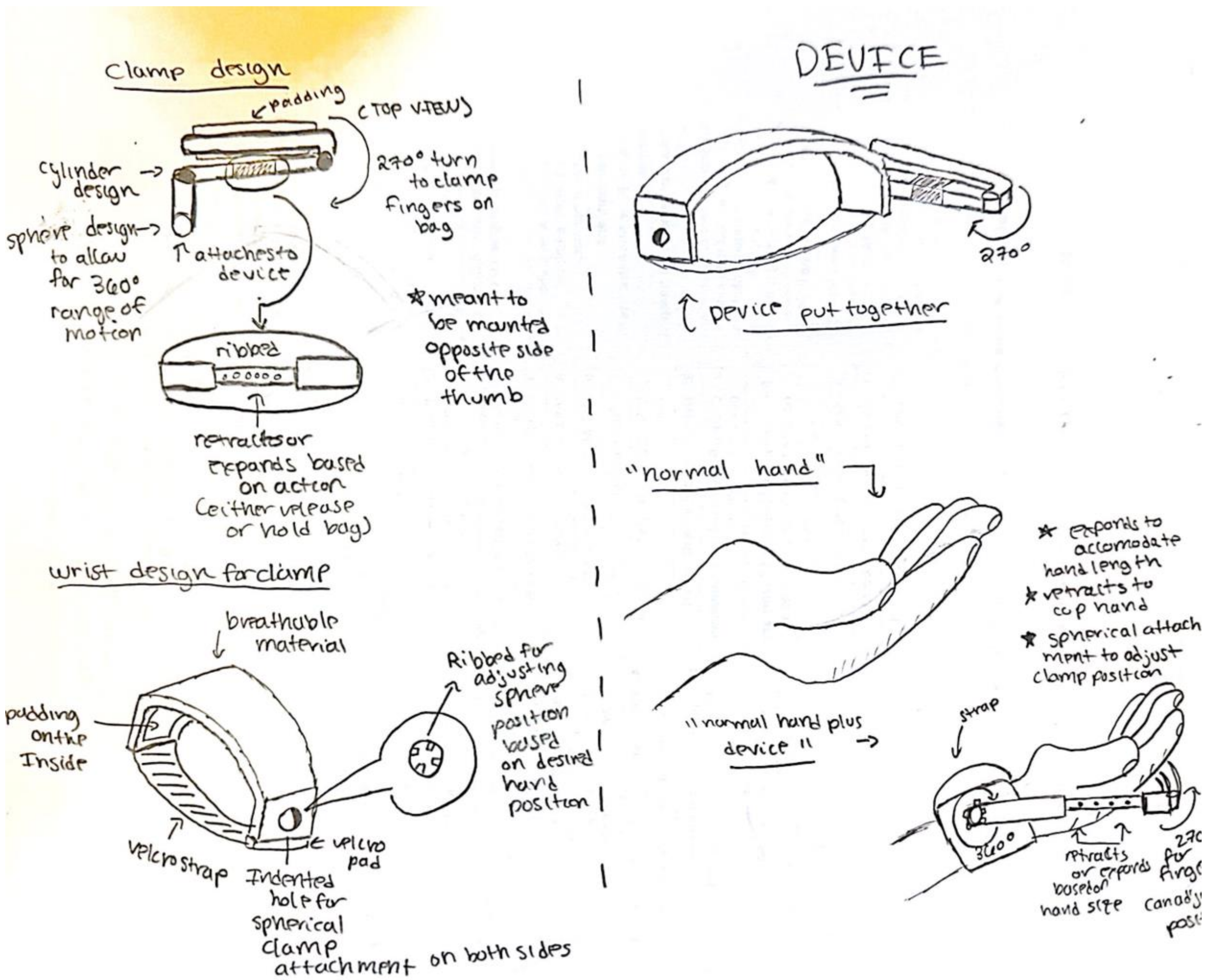


Figure C-1: Mechanical Clamp

Figure C-2. Shovel Design.

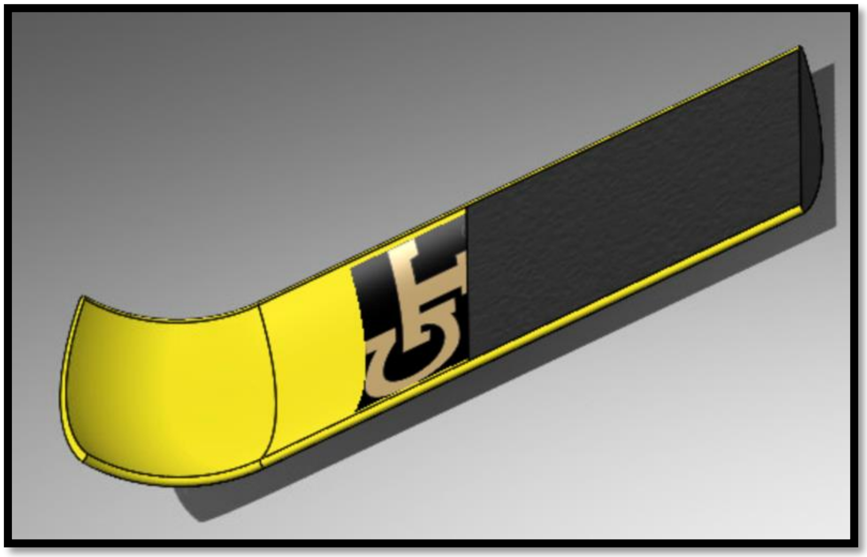


Figure C-3. Modified Shovel Design

Figure C-4. Shovel with Wrist Brace

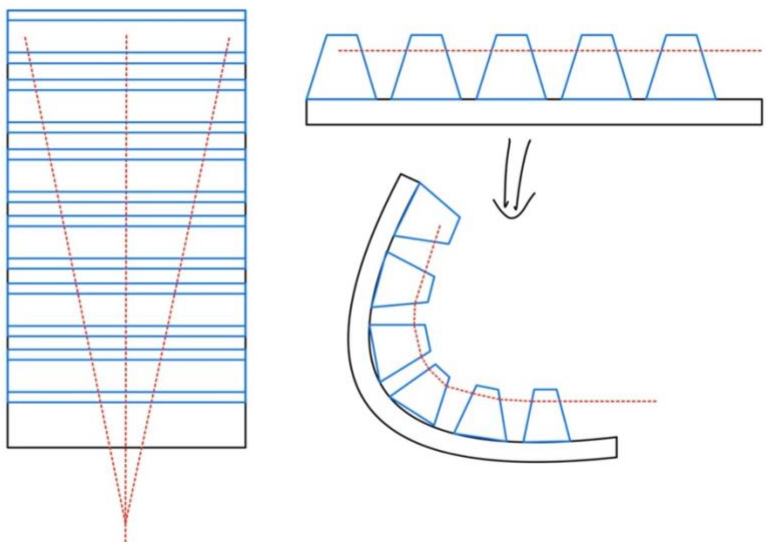


Figure C-5. Bendable Shovel Design

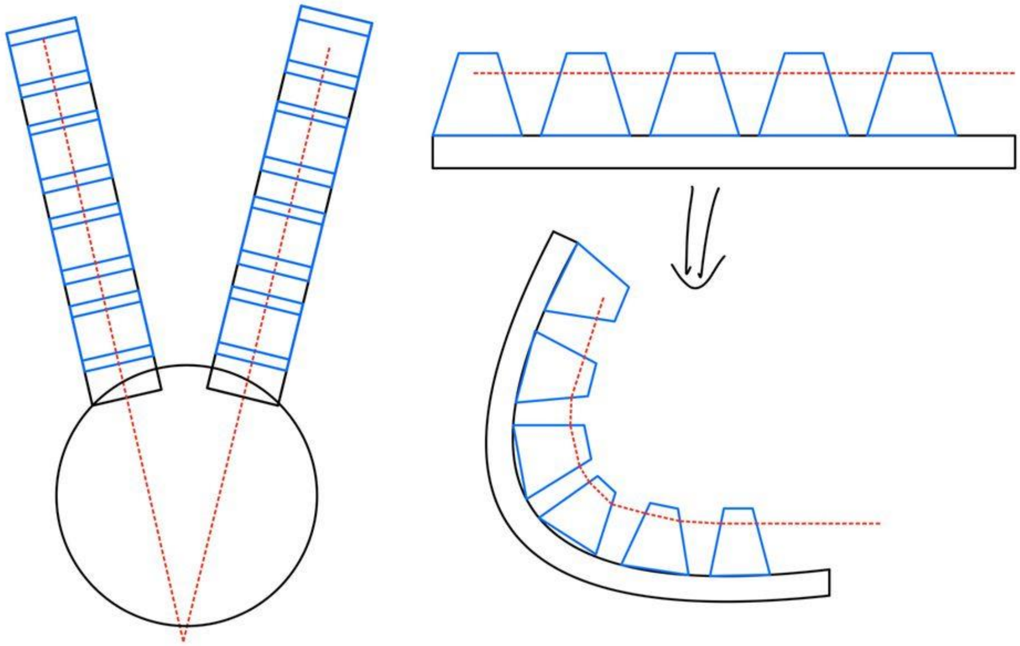


Figure C-5. Underactuated Gripper Design

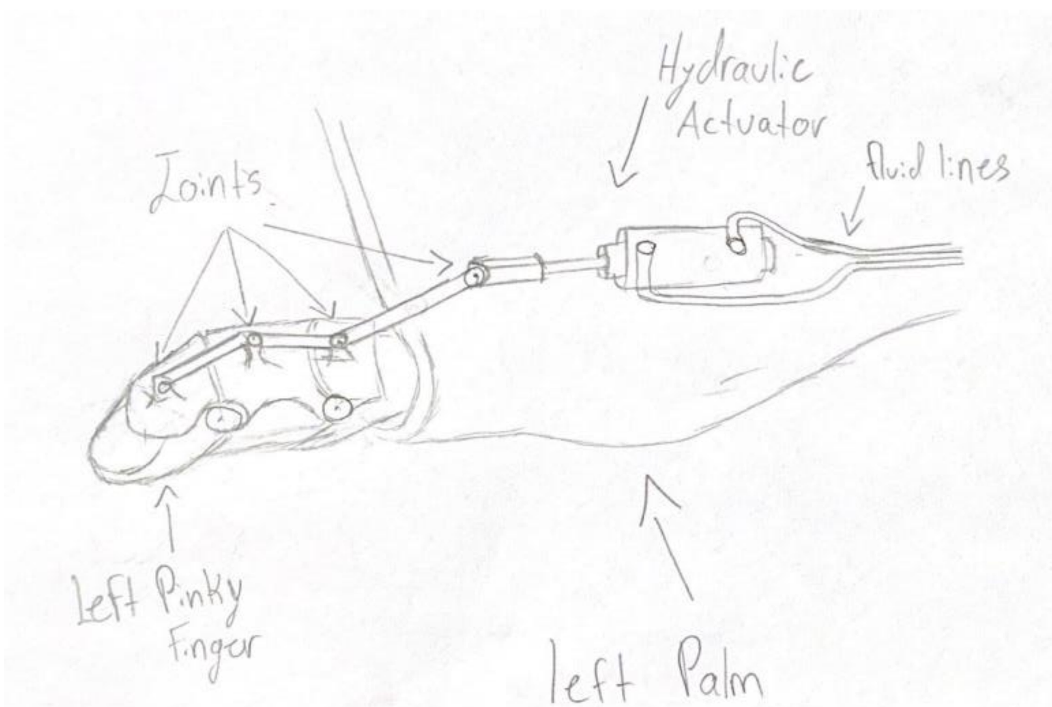


Figure C-7. Hydraulic Actuating Glove

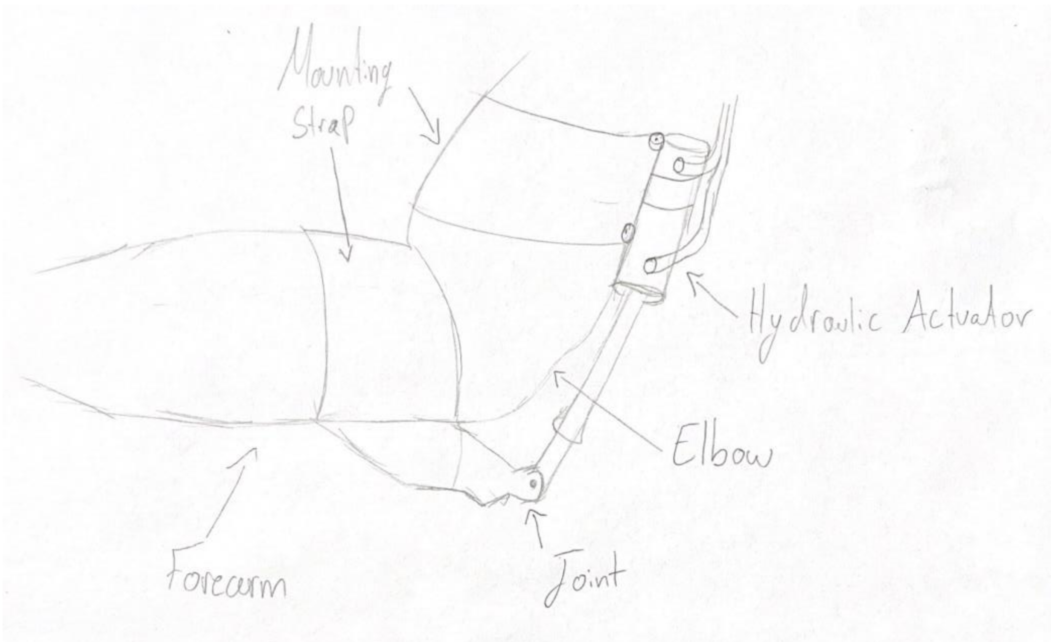


Figure C-8. Elbow Actuator

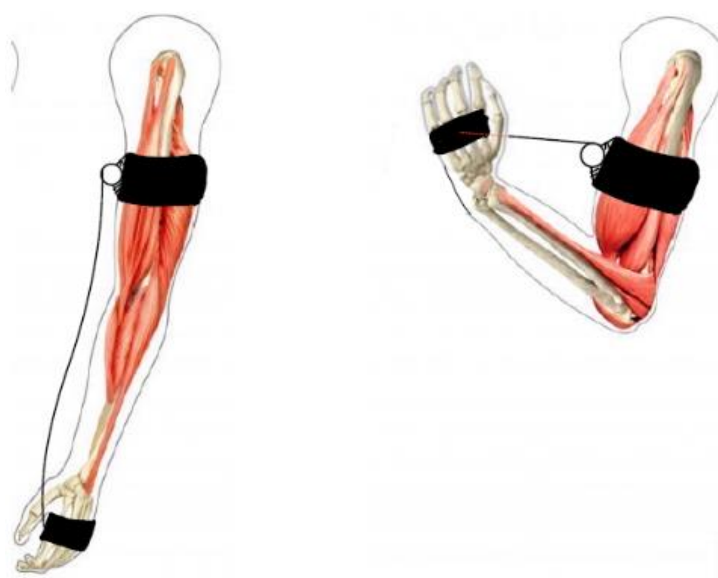


Figure C-9. Motor roller

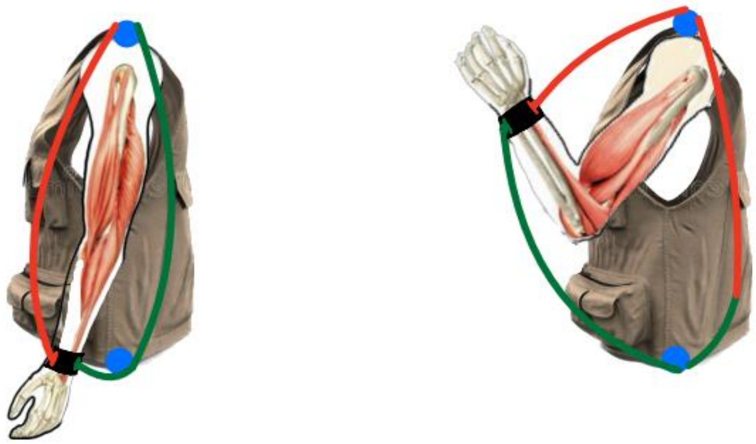


Figure C-10. Fixed belt length design

Figure C-11. External Device

CONCEPT DESIGN

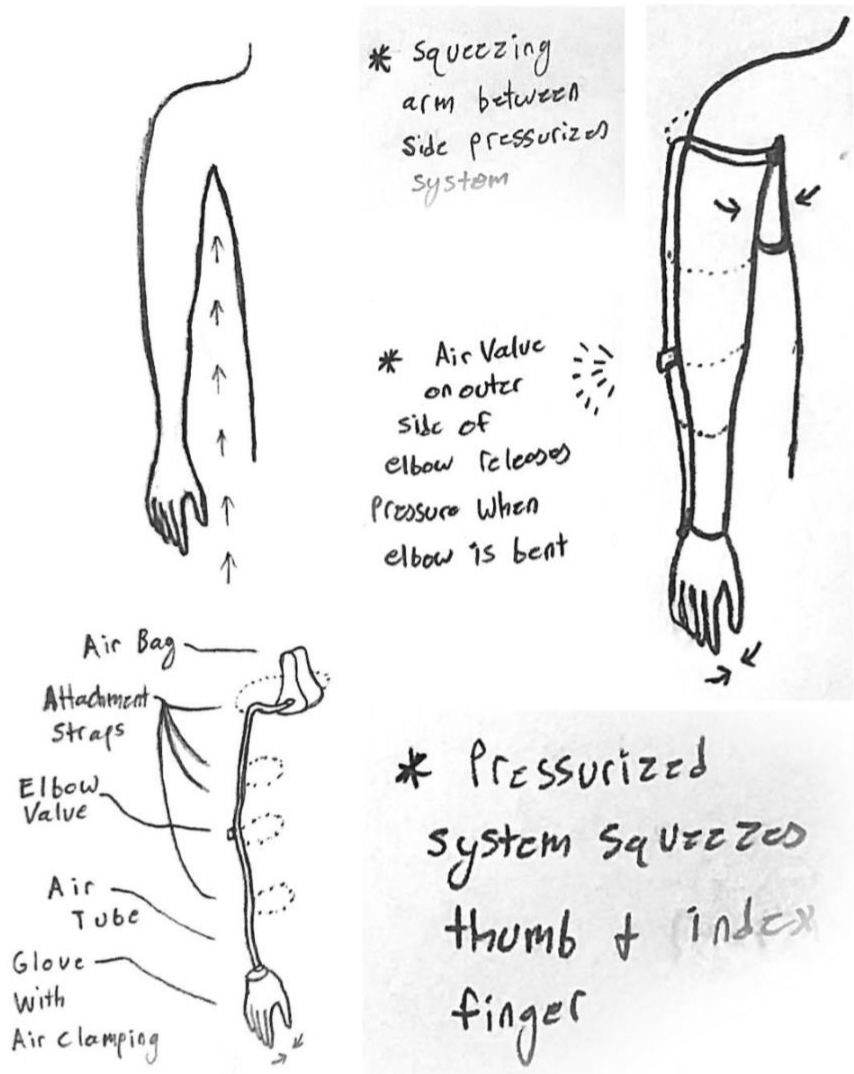
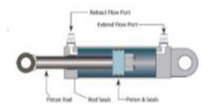


Figure C-12. Pressurized Mobility System

Ability to grab/release bag	
Shovel	
Hydraulics	
Clamps	
Magnets	

Ability to Throw	
Catapult	
Spring	
Motor	
Actuator	

Table C- 1. Morphological Chart

Appendix D: Feasibility Assessment

Table D1. Shovel Device Performance and User Ratings: Empirical Test Results.

Participant #	Trial 1	Trial 2	Trial 3	Rating
1	-0.2	0	0.5	7
2	0.1	0	0	8
3	0	-0.2	0.3	5
4	0	0.07	0	8
5	-0.1	0.2	0	7
6	0.1	0.15	-0.3	3
7	-0.07	0	0.12	6
8	0.1	0.05	0	7
9	1	-0.5	0	8
10	0	0.05	0	9

Code D-1. Analyzing the Feasibility and Stability of a Holding Mechanism for Cornhole Bags using MATLAB

```
%% Inputs
height_sitting_m = 0.5;
height_shoulder_m = 0.654;
length_arm_m = 0.749;

length_shovel_m = 0.1;
radius_shovel_m = 0.1;
angle_shovel_deg = 60;

weight_bag_kg = 0.453592;

target_distance_m = 3;
angle_launch_arm_deg = 50;
angle_launch_actual_deg = angle_launch_arm_deg + angle_shovel_deg - 90;

% friction
coeff_static_friction = 0.6; % PVC

%% Calculations

% body
x_start = 0;
x_end = 0;
y_start = height_sitting_m;
y_end = y_start + height_shoulder_m;

% arm
x_start = x_end;
x_end = length_arm_m * sind(angle_launch_arm_deg);
y_start = y_end;
y_end = y_start - length_arm_m * cosd(angle_launch_arm_deg);

% shovel
x_start = x_end;
x_end = x_end + (length_shovel_m + radius_shovel_m * sind(angle_shovel_deg))
* sind(angle_launch_arm_deg);
y_start = y_end;
y_end = y_start - (length_shovel_m + radius_shovel_m *
sind(angle_shovel_deg)) * cosd(angle_launch_arm_deg);

angle = (0:1:angle_shovel_deg) - (90 - angle_launch_arm_deg) - 90;
center_x = x_end + radius_shovel_m * cosd(angle_launch_arm_deg);
center_y = y_end + radius_shovel_m * sind(angle_launch_arm_deg);

x_end = center_x + radius_shovel_m * cosd(angle(end));
y_end = center_y + radius_shovel_m * sind(angle(end));

release_displacement_m = x_end;
release_height_m = y_end;

% linear motion
syms v_ms t_s
[t_s, v_ms] = solve(release_height_m + v_ms*t_s*sind(angle_launch_actual_deg)
- 9.81/2*t_s^2 == 0, ...
```

```
                    v_ms * t_s * cosd(angle_launch_actual_deg) ==
target_distance_m - release_displacement_m);
v_ms = double(v_ms(2));
t_s = double(t_s(2));

% angular motion
F_rot_N = weight_bag_kg * v_ms ^2 / length_arm_m;
F_x_rot_N = F_rot_N * cosd(angle_launch_actual_deg);
F_f_rot_N = F_rot_N * sind(angle_launch_actual_deg) * coeff_static_friction;

F_g_N = 9.81 * weight_bag_kg;
F_x_g_N = F_g_N * cosd(angle_launch_actual_deg + angle_shovel_deg);
F_f_g_N = F_g_N * sind(angle_launch_actual_deg + angle_shovel_deg) *
coeff_static_friction;

canRelease = (F_x_rot_N - F_f_rot_N) + (F_x_g_N - F_f_g_N) > 0;

% bottom
B_F_x_g_N = F_g_N * cosd(angle_shovel_deg);
B_F_f_g_N = F_g_N * sind(angle_shovel_deg) * coeff_static_friction;
isStable = (B_F_f_g_N - B_F_x_g_N) > 0;

display(strcat('canRelease:', num2str(canRelease), '  /  isStable:',
num2str(isStable)));
```

Equation D-1. the torque required to achieve the terminal velocity necessary for the cornhole bag to travel the necessary distances.

$$V\cos\alpha\frac{V\sin\alpha+\sqrt{(V\sin\alpha)^2+2gh}}{g}$$

Table D-2. Experimental Results from External Device Experiment

Participant #	Trial 1	Trial 2	Trial 3	Rating
1	-3	2	1	6
2	-4	1	O	5
3	1	3	1	6
4	O	-2	0.5	7
5	-2	3	-1	4
6	-0.7	O	2	6
7	0.3	-3	0.6	5
8	0.5	O	1	9
9	O	-0.8	O	8
10	-0.5	0.2	-0.4	7

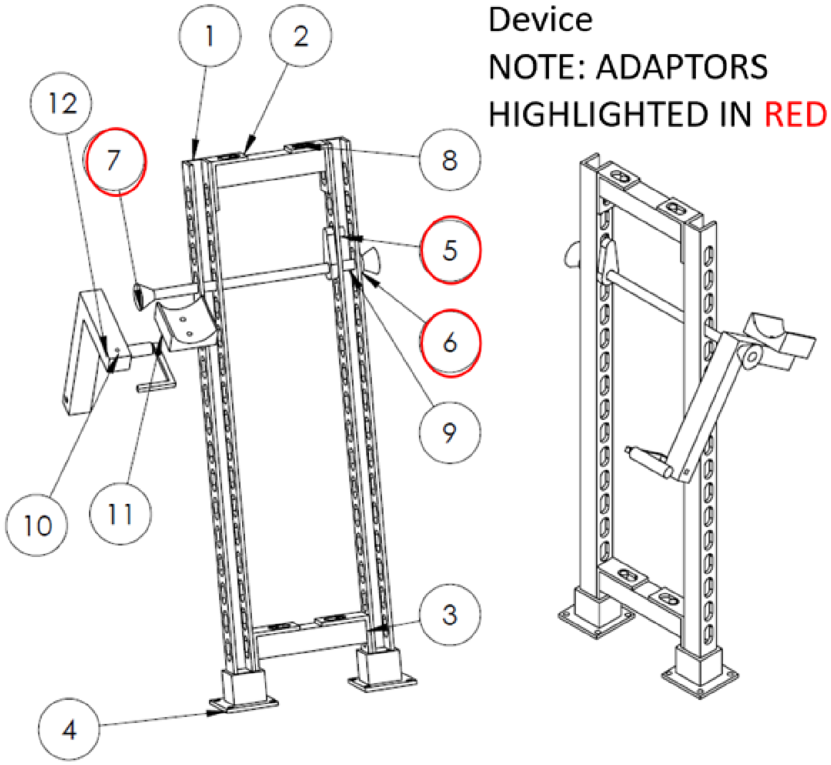
Appendix E: Final Design Solution

Figure E-1. External Device

Figure E-2. Final Shovel Prototype

Full Assembly of External Device

NOTE: ADAPTORS HIGHLIGHTED IN RED



No.	Dwg. No.	Description	Qty.
1	B5	Strut Channel Beam	2
2		L-Bracket	2
3		Metal Beam	2
4		Mount	2
5	B6	Adapter	1
6		Ball Bearing	1
7		Rubber Stopper	2
8		L-Bracket	2
9	B4	Pivot-Rod	1
10	B3	Push-Arm	1
11	B1	Arm-Rest-Plate	1
12	B2	Handle	1

NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

By: James Boatwright

TITLE:

External Device Assembly

SIZE A | DWG. NO. | REV

SCALE: 1:16 | WEIGHT: | SHEET 1 OF 1

Figure E-3. External Device Adaptors

Figure E-4 First shovel prototype

Figure E-5. Second Shovel Prototype

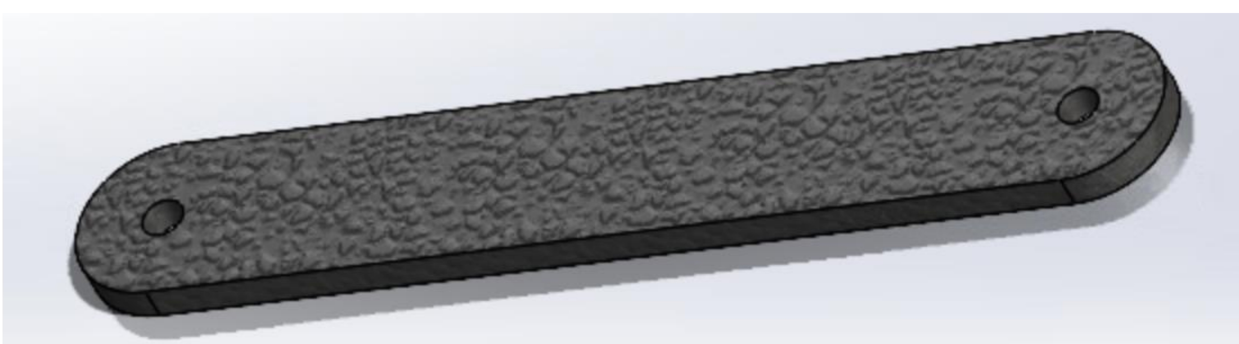


Figure E-6. Brace Support Adaptor

Appendix F: Risk Analysis

Table F-1 FMEA for Shovel Device: Analysis of Potential Failure Modes, Effects, and Mitigation Strategies

System	shovel	FMEA Number	2
Subsystem	Shovel	Prepared By	
Component	Shovel Brace Adaptor, Brace, Scoop, Fastene	FMEA Date	2023-03-15
Design Lead	Jesus, Min-Geun, Diego	Revision Date	2023-04-20
Core Team	Jesus, Min-Geun, Diego	Page	1 of 1

Potential Failure Mode and Effects Analysis (Design FMEA)

Key Date 2023-04-20

Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Prob	Current Design Controls	Det	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	New Sev	New Occ	New Det	New RPN
Adaptor used to attach Shovel scoop to arm brace	Shovel can disatach from wrist support. Adaptor material can crack	Bodily harm to forearm and wrist	3	Fractures on adaptor around bolts due to weak material or load too large.	3	crack, stress testing	5	45	Use material strongh enough to resist higher than expected applied forces	2023-04-14	Have 10% infill with gyroid pattern, use PETG	3	3	1	9
Scoop used to pick up bean bag and toss it at desired distance by user	Shear forces can casue scoop to crack and break off	Can damage patient's ligaments	8	Material is not strong enough to resist applied load forces	3	fracture, stress testing	6	144	Use material strongh enough to resist higher than expected applied forces	2023-04-14	Have 10% infill with gyroid pattern, use PETG	8	4	1	32
Fastening bolts and nuts	Bolts can loosen during use, shovel will disatach from brace.	Cause harm to user or others around	4	Nuts loosen off bolts.	5	deformation of bolts, stress testing	4	80	Use locking nuts and adheasive.	2023-04-14	Use Locking Nuts	4	8	1	32
Brace	Brace material can tear where it is attached to the adaptor	Bodily harm to forearm, wrist, and hand	5	material not sutable to resist tears once modified	3	cracking or tearing, stress testing	8	120	Reinforce the modified area to sustain tearing or craking.	2023-04-14	Reinforced the area by better finishing	5	3	2	30

Table F-2 FMEA for External Device: Comprehensive Evaluation of Risks, Consequences, and Recommended Actions.

System	External Device		FMEA Number: 2
Subsystem	Weighted Mass, Launching Pad, Swing	**Potential Failure Mode and Effects Analysis (Design FMEA)**	Prepared By:
Component	Mass Inserts, Orthotic Interface, Bottom platform, Swing		FMEA Date: 2023-03-06
Design Lead	James, Sanghyub, Sufiyan	Key Date: 2023-04-15	Revision Date: 2023-04-15
Core Team	James, Sanghyub, Sufiyan		Page 1 of 1

Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	Prob	Current Design Controls	Det	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Action Results: Actions Taken	New Sev	New Occ	New Det	New RPN
Swing is used to provide height for sufficient placement for the user sitting on wheel chair.	The swing can fracture from the force to push and the users arm.	The failure of the swing can lead to structural collapse of the entire system which can endanger the user and the surroundings.	8	The weakened structural support of the weight and force loading mechanism can cause the failure of the following structure.	2	Accurate calculation of the mass and the user's arm and force load on each joint is measured to ensure the safety of the structure.	2	**32**	Careful material selection and joint structure design are required to ensure the success of the swing.	2023-03-29	Used Iron cast that has high elastic modulus for the beams. Use light materials for the swing	8	1	1	8
Ground Platform is used to add stability to entire structure.	The base could become unstable and collapse.	If the structure collapses it could cause damage.	7	Poor stability on base structure.	3	Current design for the base is fairly simple, making it easy to detect any possible failure as it can be easily tested via inspection.	1	**21**	Extend the base in a direction parallel to the swing. Lighten the swing	2023-03-29	The power of the swing was changed to human power rather than weight.	7	1	1	7

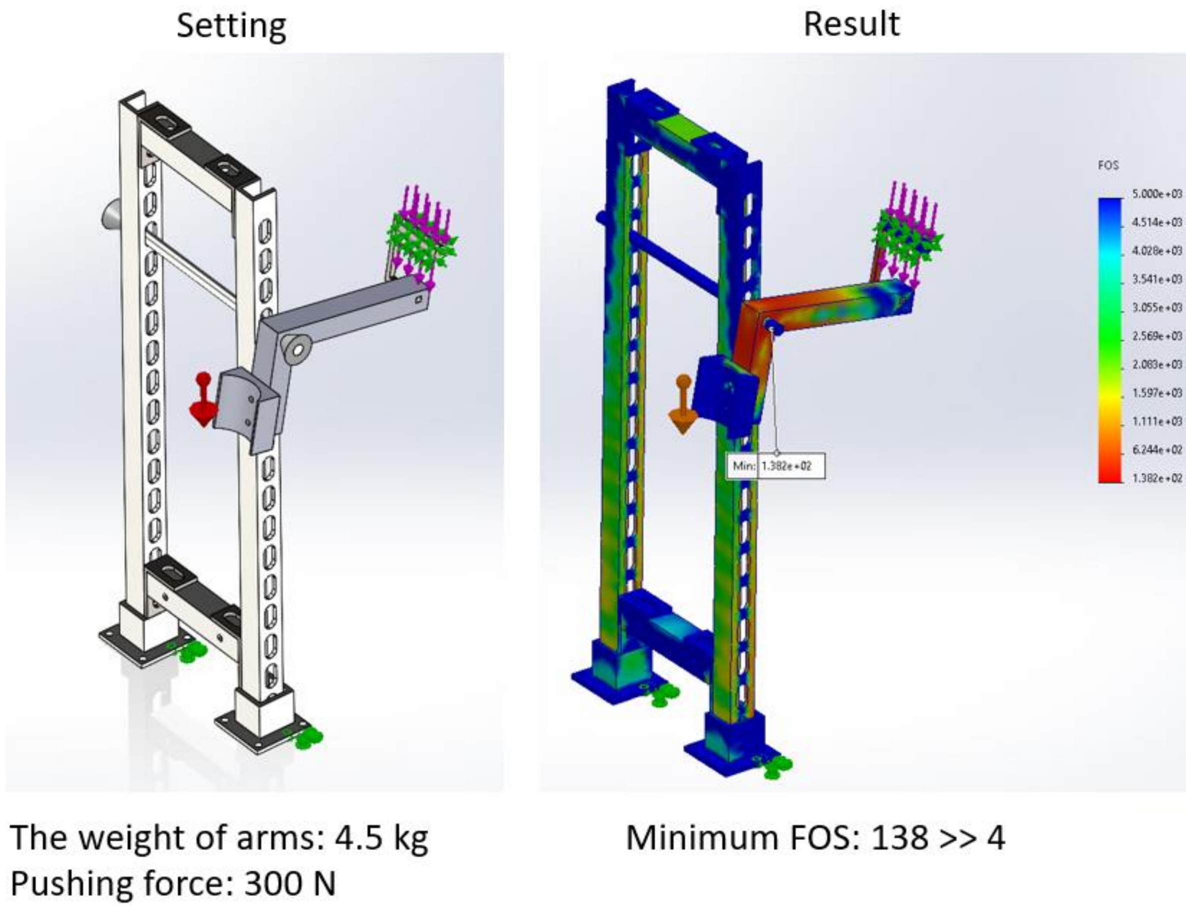
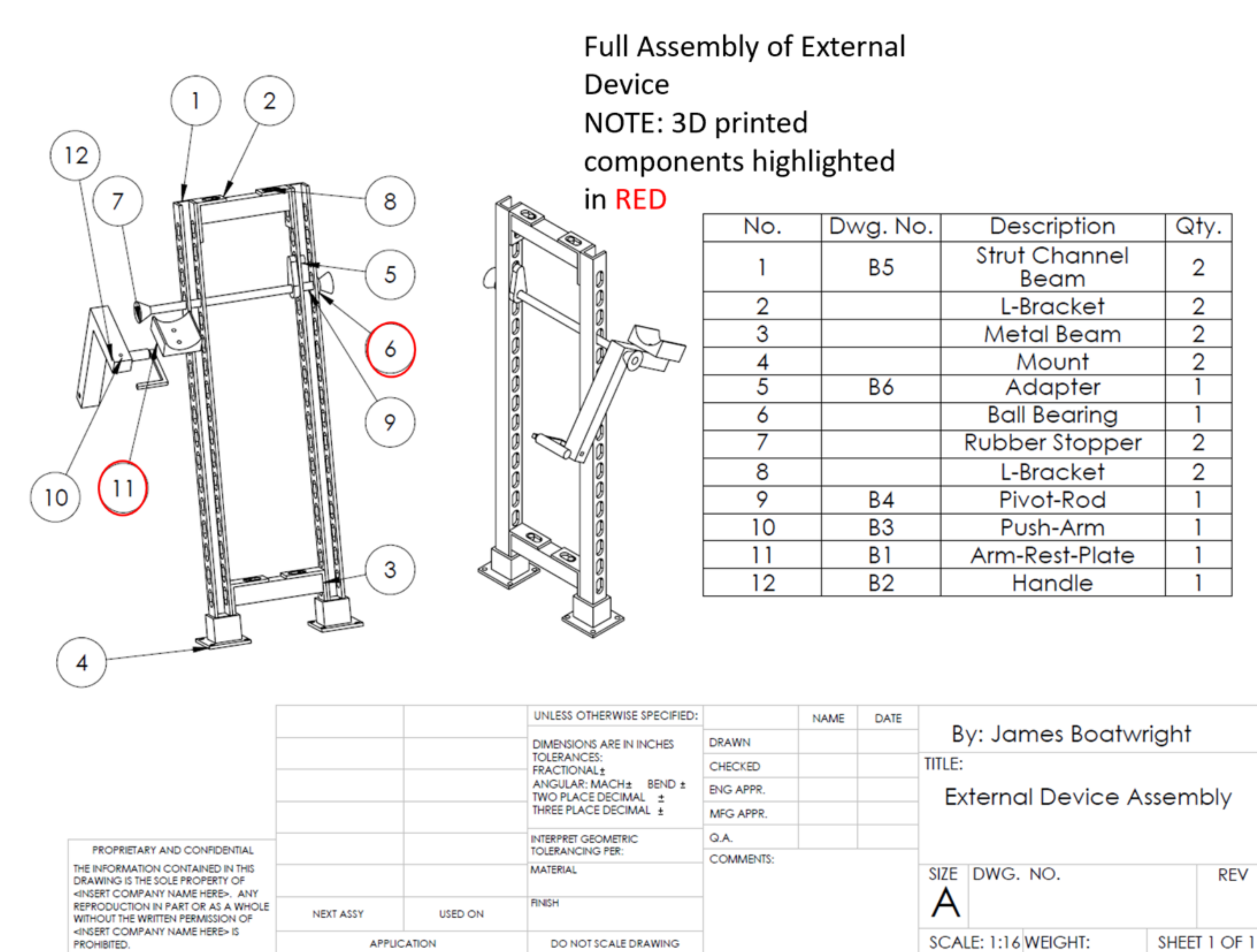


Figure F-1. SolidWorks FOS Simulation - Displaying stress distribution and critical areas in the external device's components, confirming structural integrity and user safety.

Appendix G: Manufacturing



No.	Dwg. No.	Description	Qty.
1	B5	Strut Channel Beam	2
2		L-Bracket	2
3		Metal Beam	2
4		Mount	2
5	B6	Adapter	1
6		Ball Bearing	1
7		Rubber Stopper	2
8		L-Bracket	2
9	B4	Pivot-Rod	1
10	B3	Push-Arm	1
11	B1	Arm-Rest-Plate	1
12	B2	Handle	1

Figure G-1. 3-D printed components for External Device

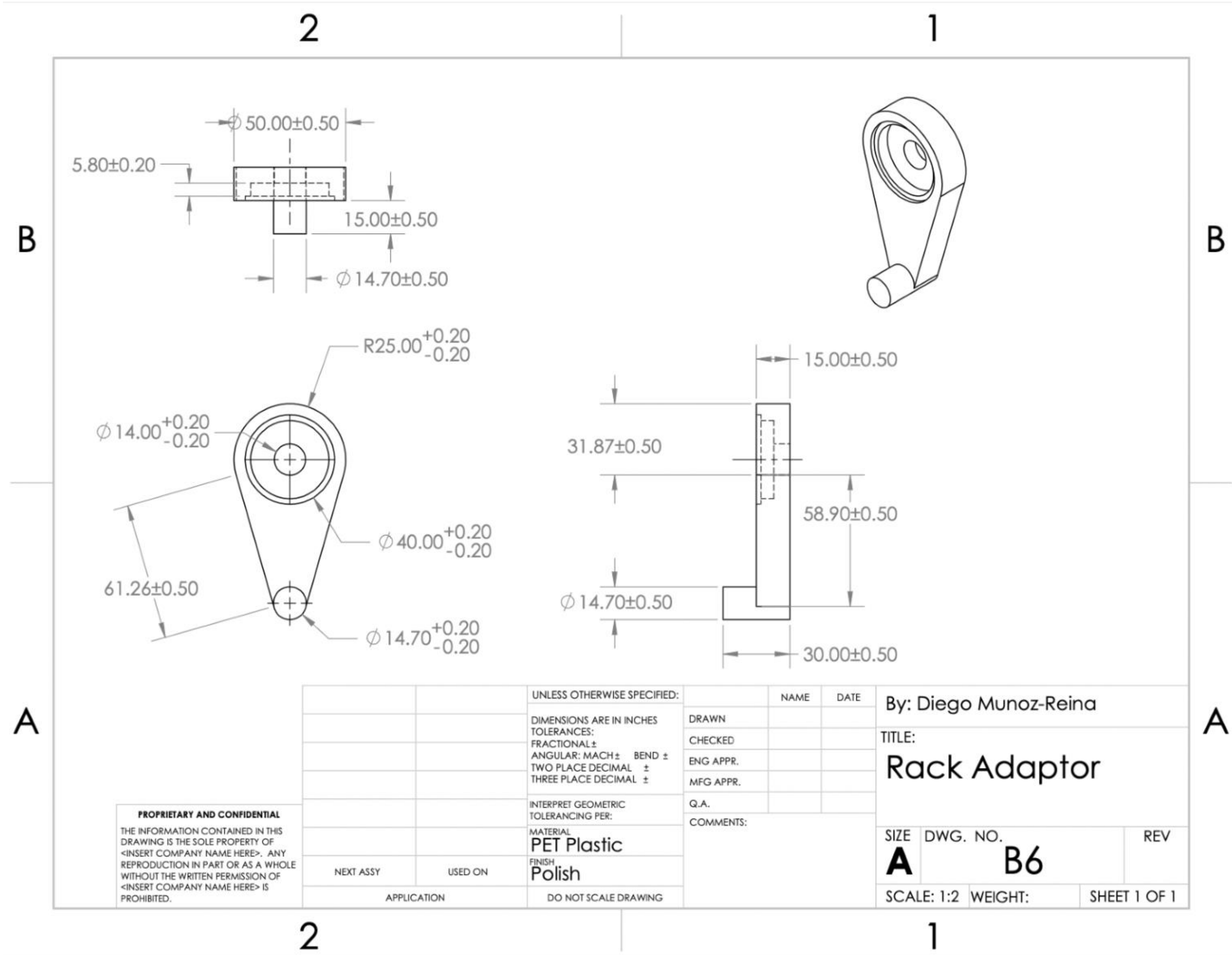


Figure G-2. Adaptor Drawing and Tolerances

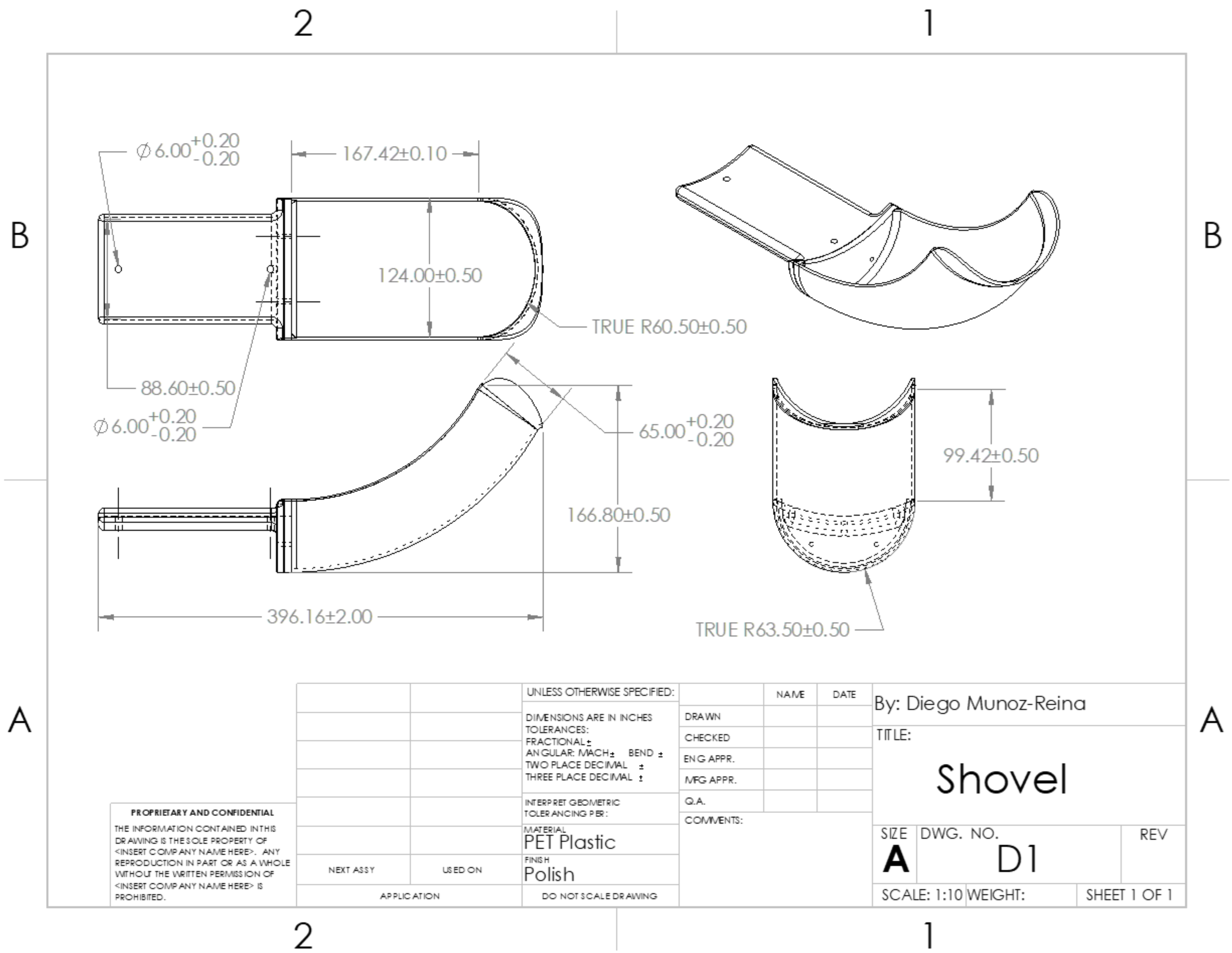


Figure G-3. Shovel Drawing and Tolerances

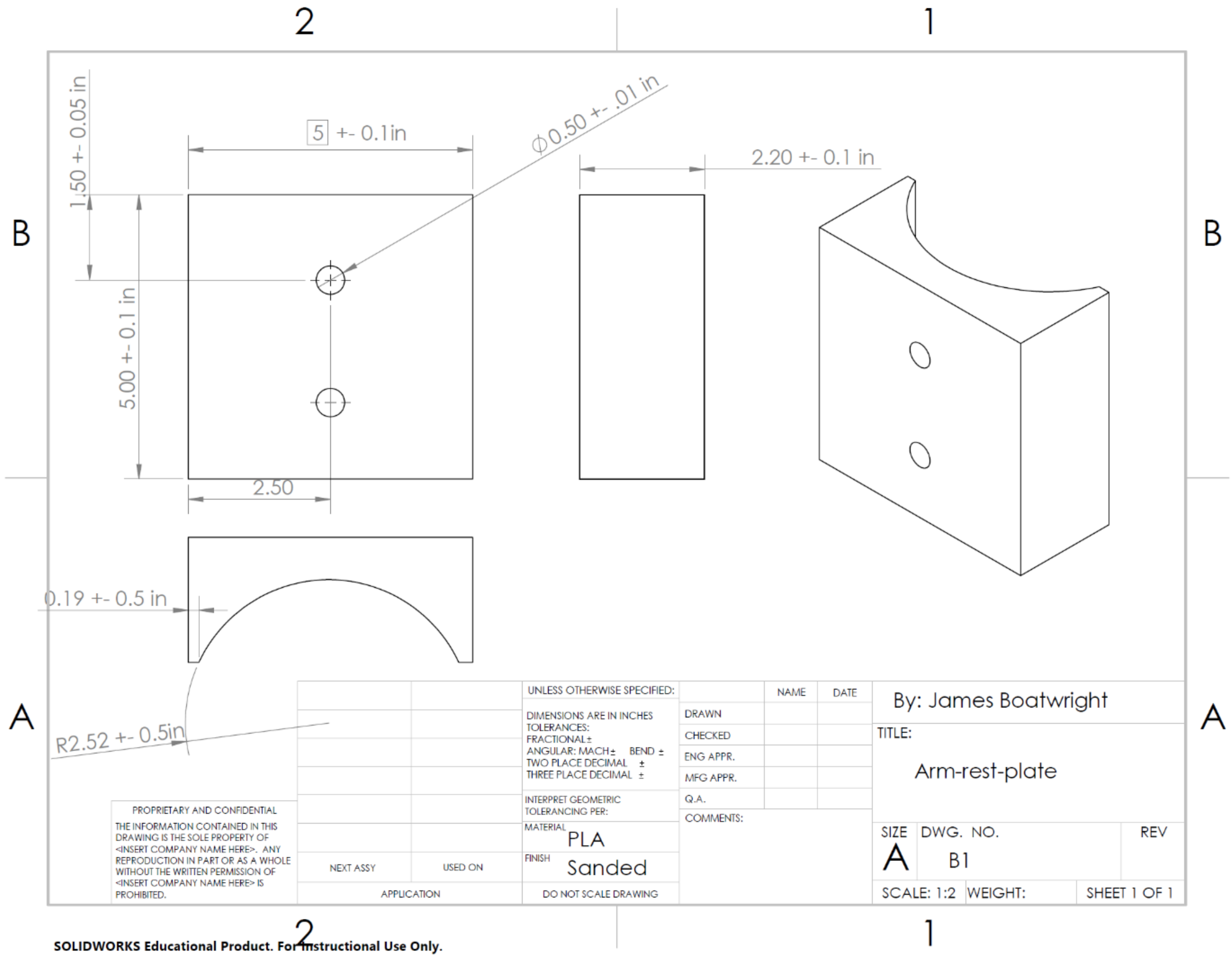


Figure G-4. Arm Rest Plate Drawing and Tolerances

Table G-1: Production Cost Analysis

Particulars: External Device	Value:	Particulars: Shovel Device	Value:
Raw Materials	$159.46	Raw Materials	$21.50
Labor Cost	$50	Labor Cost	$10
Product Cost	$209.46	Product Cost	$31.50